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ARL-SYS-TM-128

AR-006-065

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MELBOURNE, VICTORIA

Aircraft Systems Technical Memorandum 128

PERSPECTIVE TRANSFORMATION FOR

WIDE-VIEW SKY SCENES

by

L.N. Lester

Approved for public release.

FEBRUARY 1990

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SUMMARY

Fixed vantage point simulation requires a wide field of view for the external visual environment. The sky scene, however, is of secondary importance as moving objects in the scene are the areas of interest. It is therefore cost-effective to represent the sky in such cases as a two dimensional spherical surface enclosing the earth. This memorandum derives the perspective transformation necessary to project points from this sphere onto two dimensional viewing screens. Inversion of this transformation is also presented.

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TABLE OF CONTENTS

Page Number

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DOCUMENT CONTROL DATA SHEET

1. INTRODUCTION

Fixed vantage point simulators, such as battlefield or air traffic control tower visual simulators, require wide field of view sky scenes (up to 360° in azimuth) for realistic presentation. Production of a three dimensional sky image using computer generated imagery would be computationally expensive. Since moving objects in the scene delineate the areas of interest, the sky scene itself is of secondary importance, and can be represented as a two dimensional surface around the earth. This can be accomplished by treating the earth as a sphere, with the sky/cloud base as another sphere enclosing the earth.

This memorandum derives the perspective transformation necessary to project points from the cloud base sphere onto two dimensional screens for viewing. However, as elevation decreases towards the horizon, larger regions of the cloud base sphere are represented by the same area measure on the two dimensional screen. It is therefore more appropriate to compute pictures by starting with pixels on the two dimensional screen, and finding the cloud sphere regions to which they correspond. These can then be used to determine the pixels' colour. This approach requires the inversion of the perspective transformation, and is discussed following the derivation of the perspective transformation.

2. PERSPECTIVE TRANSFORMATION

It is assumed that the field of view is divided among a number of two dimensional viewplanes, so that each viewplane spans an angle of α in azimuth. Let β be the elevation angle spanned from the horizon upwards. Each viewplane has its own two dimensional coordinate system, $X_s Y_s$, with origin at the bottom left corner as seen by an observer. X_s increases to his right, and Y_s increases upwards, so that values near zero represent points on the left, near the horizon. Coordinates in this system are dimensionless, and lie in the range 0 to 1. We also define a three dimensional coordinate system, $X_c Y_c Z_c$, with origin centred at the observer's eye. X_c points out of the centre of one of the viewplanes, Z_c points downward, and Y_c is such that the resulting system is right handed. Coordinates in this system are expressed in kilometres. Figure 1 illustrates the case for the viewplane containing the X_c-axis. O is the eye of the observer and $KLMN$ is the viewplane.

To formulate the perspective transformation, consider the line of sight to a point $P(x_c, y_c, z_c)$ on the cloud layer – the line OP in Figure 1, which intersects the viewplane at I. Looking in the X_c-Z_c plane (see Figure 2), P' is the projection of P, and I' the projection of I. C is the centre of the earth, H the horizon, KL the edge of the viewplane and $\angle LOK = \beta$, the elevation from the horizon upwards. Now, the normalised viewplane coordinate, y_s, is

Cloud base
sphere

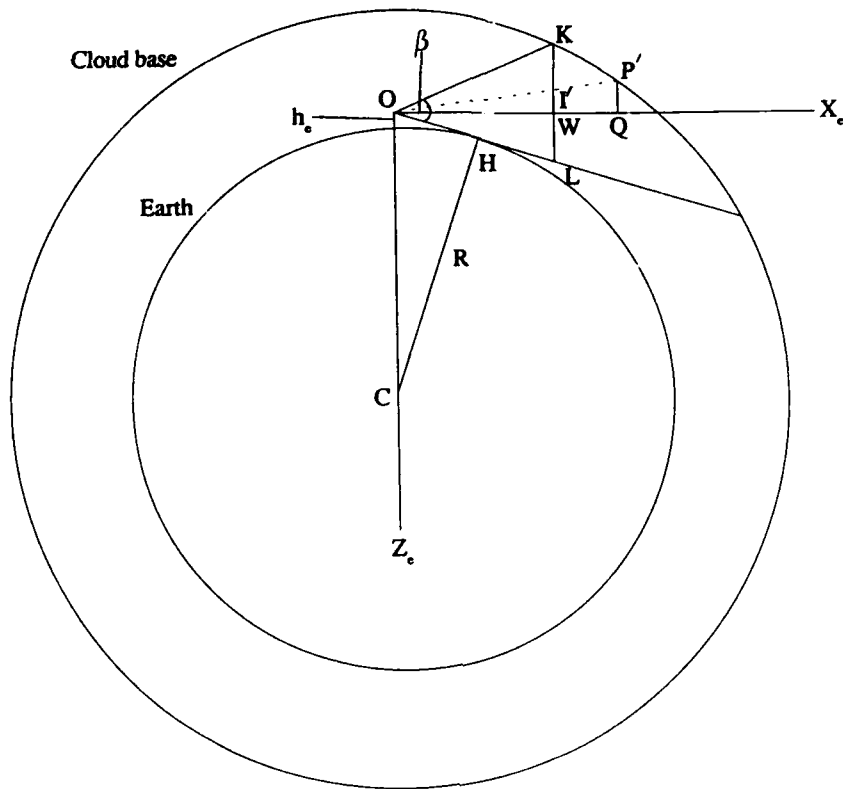Horizon

FIG. 1 CLOUD SPHERE AND VIEWPLANE CONTAINING X_e-AXIS

FIG. 2 EARTH AND CLOUD SPHERES IN THE X_e-Z_e PLANE

the distance LI', divided by the viewplane height, LK. In terms of distances to the X_c-axis,

$$y_s = \frac{LI'}{LK} = \frac{LW + WI'}{LW + WK} \qquad (1)$$

where W is the point at which KL intersects the X_c-Y_c plane. Since $LW = OW \tan \angle LOW$, $WI' = OW \tan \angle WOI'$ and $WK = OW \tan \angle WOK$, then

$$y_s = \frac{OW \tan \angle LOW + OW \tan \angle WOI'}{OW \tan \angle LOW + OW \tan \angle WOK} = \frac{T_L + \tan \angle WOI'}{T_L + T_W} \qquad (2)$$

where $T_L = \tan \angle LOW$ and $T_W = \tan \angle WOK$. Now, $\angle LOW = \angle OCH$, and in triangle OCH, $CH = R$, the earth radius, and $OC = R + h_c$, the height of the observer's eye above the earth centre (h_c is the height of the observer's eye above the earth's surface.) Thus,

$$T_L \equiv \tan \angle LOW = \tan \angle OCH \approx \sqrt{(R + h_c)^2 - R^2}/R. \qquad (3)$$

$\angle WOK = \beta - \angle LOW$, so

$$T_W \equiv \tan \angle WOK = \frac{\tan \beta - T_L}{1 + T_L \tan \beta} \qquad (4)$$

The coordinates of P are used to determine $\tan \angle WOI'$, which is the same as $\tan \angle P'OQ$ in Figure 2. Thus,

$$\tan \angle WOI' = -z_c/x_c. \qquad (5)$$

The negative sign arises because Z_c points downward, whereas the distance PQ is measured in the opposite sense. The viewplane coordinate, y_s, is therefore given by

$$y_s = \frac{T_L - \frac{z_c}{x_c}}{T_L + T_W} \qquad (6)$$

where T_L and T_W are given by (3) and (4).

To determine the normalised coordinate, x_s, consider the X_c-Y_c plane as shown in Figure 3. ML is the bottom edge of the viewplane, and intersects the X_c-Z_c plane at J. Coordinate x_s is the distance MI'' divided by the viewplane width, ML. That is,

$$x_s = \frac{MI''}{ML} = \frac{MJ + JI''}{2MJ} = \frac{1}{2}\left(1 + \frac{JI''}{MJ}\right) \qquad (7)$$

Using the coordinates of P (triangle OJM) gives
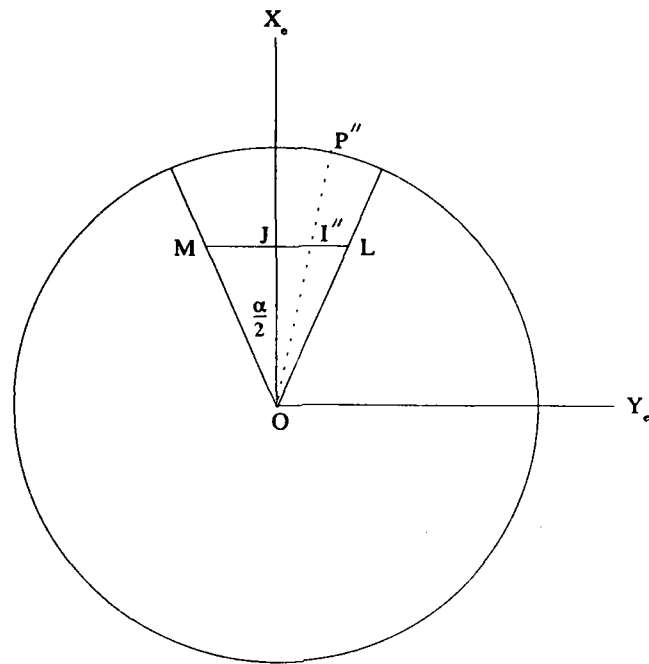
$$\frac{JI''}{OJ} = \frac{y_c}{x_c} \qquad (8)$$

FIG. 3 LOOKING DOWN ON THE VIEWPLANE CONTAINING X_e-AXIS

and from triangle OJM,

$$OJ = MJ \cot(\alpha/2). \tag{9}$$

Using (9) and (8) in (7) gives

$$x_s = \frac{1}{2}\left(1 + \frac{y_c}{x_c} \cot \frac{\alpha}{2}\right). \tag{10}$$

The perspective transformation for the viewplane containing the X_e-axis is thus given by (6) and (10). For the other viewplanes, it is necessary to rotate that screen into the one with the X_e-axis before applying the transformation. This rotation is about the Z_e-axis thus:

$$x'_e = x_e \cos \omega - y_e \sin \omega$$
$$y'_e = x_e \sin \omega + y_e \cos \omega$$
$$z'_e = z_e \tag{11}$$

where ω is the angle required to rotate a viewplane into coincidence with the one containing the X_e-axis. To determine this angle, $\tan^{-1}(y_c/x_c)$ is examined as a four quadrant angle. If this is between $\pm\alpha/2$, then it is the X_c-axis viewplane and $\omega = 0$. If the angle is between $\alpha/2$ and $3\alpha/2$, it is the next viewplane and $\omega = -\alpha$. Similar reasoning applies for the other viewplanes. Having performed the appropriate rotation, the perspective transformation is applied to (x'_e, y'_e, z'_e) through (6) and (10).

3. INVERTING THE PERSPECTIVE TRANSFORMATION

In producing wide field of view scenes, it may be more appropriate to approach the problem in a manner similar to that used in ray tracing, where tracing starts at the viewpoint and rays are traced backwards through each pixel to their origin (Ref. 1). In this case, a pixel on the two dimensional viewplane would be mapped into a region on the cloud sphere, with that region being used to determine the pixel's colour.

To achieve this, it is necessary to invert the perspective transformation, so that given viewplane coordinates (x_s, y_s), and which viewplane it is, the cloud sphere coordinates, (x_c, y_c, z_c) can be found. Generally, this is not possible because the perspective transformation loses information. In this case, however, the required point lies on the cloud sphere, whose equation is

$$x_c^2 + y_c^2 + [z_c - (R + h_c)]^2 = (R + h_c)^2 \tag{12}$$

where h_c is the height of the cloud sphere above the surface of the earth. Rearranging (6) and (10) for the viewplane containing the X_c-axis give z_c and y_c in terms of x_c thus:

$$z_c = x_c [T_L - y_s(T_L + T_W)]$$
$$y_c = x_c \tan \frac{\alpha}{2}(2x_s - 1) \tag{13}$$

Substituting these into (12) gives:

$$x_c{}^2\{1 + \tan^2 \frac{\alpha}{2}(2x_s - 1)^2 + [T_L - y_s(T_L + T_W)]^2\}$$
$$- 2(R + h_c)x_c[T_L - y_s(T_L + T_W)]$$
$$+ (R + h_c)^2 - (R + h_c)^2 = 0 \tag{14}$$

Solution of this quadratic gives two values for x_c, representing opposite points on the cloud sphere. For this viewplane, however, the solutions will be of opposite sign, and since x_c is always positive in this viewplane, the negative solution can be eliminated. We thus have a unique value for x_c, which can be substituted into (13) to obtain the y_c and z_c values.

Having determined the coordinates corresponding to (x_s, y_s) for the viewplane containing the X_c-axis, the cloud sphere coordinates can now be obtained by rotating these coordinates about the Z_c-axis through ω, where ω is the angle required to rotate a viewplane into coincidence with the one containing the X_c-axis:

$$x_c = x'_c \cos \omega + y'_c \sin \omega$$
$$y_c = -x'_c \sin \omega + y'_c \cos \omega$$
$$z_c = z'_c \tag{15}$$

where (x'_c, y'_c, z'_c) are the coordinates in the X_c-axis viewplane and (x_c, y_c, z_c) are the coordinates in the required viewplane.

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1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-006-065	ARL-SYS-TM-128	FEBRUARY 1990	AIR 82/140

4. TITLE	5. SECURITY CLASSIFICATION	6. NO. PAGES
PERSPECTIVE TRANSFORMATION FOR WIDE-VIEW SKY SCENES	(PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF. (C) RESTRICTED (R), UNCLASSIFIED (U)). [U] DOCUMENT [U] TITLE [U] ABSTRACT	9 7. NO. REFS. 1

8. AUTHOR(S)	9. DOWNGRADING/DELIMITING INSTRUCTIONS
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10. CORPORATE AUTHOR AND ADDRESS	11. OFFICE/POSITION RESPONSIBLE FOR:
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17. IMPRINT

AERONAUTICAL RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. COST CODE	20. TYPE OR REPORT AND PERIOD COVERED
	716881	

21. COMPUTER PROGRAMS USED

22. ESTABLISHMENT FILE REF.(S)

23. ADDITIONAL INFORMATION (AS REQUIRED)